M-C Power Commercialization Program Overview

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Introduction

Industry Environment. As the U.S. gas industry emerges from the initial uncertainty created by deregulation, utilities have developed a greater understanding of market forces. Now offering a myriad of unbundled services, the industry allows customers to pick and choose the proper combination of natural gas services at the lowest price. Understanding conditions that enable savvy competitors to prosper is also providing the gas industry with a major advantage as the electric power industry begins its transition toward competition. Competition in the electric generation market began in the 1980s, but major changes are now on the horizon. Even today, power marketers are positioning themselves for aggressive competition, even though electricity sales and distribution are still controlled by regulated electric utilities. These new players are approaching individual industrial, commercial, and even residential customers in an effort to define the opportunities being created with the unbundling and repackaging of electric energy services. As competition in the electric power market increases, there will be a downward pressure on the prices charged by the various players.

Companies that position themselves as integrated suppliers of a full-line of value-added energy services will become the winners in the evolving energy marketplace. Currently, a variety of tools help these participants be more competitive and provide lower cost of services to their customers. One technology that will enable participants to expand their role in the energy services marketplace is the molten carbonate fuel cell. Distributed power plants based on this technology are uniquely qualified to fill the demand for localized, efficient, and environmentally friendly energy supplies at the lowest possible cost to the consumers. This type of equipment will allow energy service companies to supply the majority of a customer's electric and thermal energy needs from small power plants located at the customer's facilities. These distributed resources offer benefits over and above the commodity electricity and heat produced. Reliability and quality of the electricity, utility grid support, and independence of self-generation are a few examples of these benefits.

Over the past decade the regulated electric industry was successful at establishing barriers to cogeneration and self-generation, such as supplemental, backup, and/or standby charges, modified rate structures, and project buy-outs. With full competition in the electric marketplace, some of these services will be available from competitive sources. Therefore, market forces will set the

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price and distributed generation will compete on a level playing field. For fuel cells to achieve the promise they have always had in the technologist's mind, developers must introduce products that are cost-effective and durable. M-C Power's Commercialization Team realizes that its product must compete with commodity priced energy supplies while providing customers added-value services. The commercialization program is focused on developing and verifying the technology that will allow the Team to introduce a cost-effective product with the durability demanded by the marketplace.

Objectives

M-C Power's mission is the development and subsequent commercialization of Molten Carbonate Fuel Cell (MCFC) stacks. In order to achieve this objective, M-C Power assembled a formidable team of industry leaders. The team includes, M-C Power, Bechtel Corporation, Stewart & Stevenson Services, and the Institute of Gas Technology. This group, referred to as the Commercialization Team, has developed a strategy to move decisively through the Technology Development and Product Design and Improvement stages. Successfully fulfilling the objectives of these programs will bring MCFCs to commercialization.

Product Design and Improvement (PDI) activities began in 1995 in parallel with the final steps of the Technology Development efforts. The major focus of the Product Design and Improvement activities is to address cost reduction issues and to establish the commercial readiness of the power plant, stack technology, and marketplace infrastructure. The Team's initial efforts have been to address these issues at the component level, followed by verification of advanced technologies in prototype power plant hardware.

The major barrier to successful fuel cell commercialization has been the higher first cost in comparison to conventional equipment. The molten carbonate fuel cell technology is no different, and therefore, the Team's goal must be to define and develop advanced stack and power plant technologies that allow the introduction of a cost-effective product even during the low production volumes of the initial few years.

M-C Power has defined a range of advanced technologies which have the potential to achieve this goal. These technologies address the two major cost reduction areas of the stack - separator plates and non-repeat hardware. Advanced separator plate designs reduce the number of components needed for the assembly from the fifteen pieces (used in Unocal) to two pieces. Cost reduction of the non-repeat hardware will be achieved through creative engineering efforts which eliminate hardware and integrate functions. In parallel cost reduction in the repeat components are also being examined. These include faster manufacturing processes and reduced raw material through thinner components and reduced scrap.

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Approach

Scaling-up of the Technology. During the initial technology development phase of the program M-C Power scaled-up the technology to dimensions required for cost-effective stacks. The first step involved scale-up and verification of cells with active areas approaching 1-m^2 (11-ft^2). This size enables each cell to generate between 1-kW and 1.5-kW of electricity. After verification testing of short-stacks, the technology was incorporated into full-height stacks consisting of several hundred cells. These full-height stacks were subsequently integrated into developmental power plants that are providing the initial proof-of-concept.

Much of M-C Power's scale-up activities concentrated on the successful implementation of full-size separator plate configuration. This component integrates the functions of cell-to-cell electrical connection, anode/cathode gas separation, formation of process gas flow fields, and soft-rail structures that form wet-seal barriers between internal process gas manifolds and flow fields. The separator plate is made from sheet metal, which has been pressed to form the various features and welded into a final assembly.

Scale-up of the manufacturing processes was a prerequisite to developing commercial-size cells. The world's first manufacturing facility, designed exclusively for fabricating MCFC components, was operating during the early 1990s. These processes are based on tape casting large-area porous components at widths approaching 1.3 meters (52 inches) and component thickness within plus or minus two thousandths of a centimeter. Anodes, cathodes, matrices and electrolyte tapes are all initially manufactured using this tape casting equipment. The metal components (anodes and cathodes) are then sintered in a continuous, dual atmosphere furnace resulting in high quality components with tight control of both bulk porosity and pore size distribution. The individual components are then cut to shape and added to a separator plate prior to final stack assembly.

Beginning in 1992, several short-stacks were fabricated and tested to verify M-C Power's full-scale cell components and continuous manufacturing processes. Verification involved the testing of six stacks containing 20-cells, each producing at least 20-kW of electricity. These tests proved many of the unique characteristics of M-C Power's MCFC stack design and laid the foundation for continued developments.

Program Description

Introduction. Verification tests and power plant efforts within the Product Development and Improvement program are directed toward the construction and operation of a prototype, 1-MW power plant. This unit is intended to reflect all of the design and operational features of the Team's market entry product. The first 1-MW power plant is scheduled for operation towards the end of 1998. The commercialization team has developed a strategic approach to the project implementation. The approach capitalizes on activities performed in past projects by building upon the substantial technology base already established. This approach enables the team to accelerate its efforts to satisfy our commercialization objective and successfully design, manufacture, field test, and evaluate a prototype power plant.

Product definition and market assessment. This involves the definition of a market driven power plant and the planning required to successfully introduce the power plant into the marketplace. Development of a market-driven product is enhanced by bringing the end users into early planning, product definition, and design phases. Preliminary marketplace inputs have emphasized the importance of reliability, durability, and cost. Although the initial introduction may require an elevated pricing structure in comparison to conventional technologies, reliability and durability of the power plant cannot be compromised.

Several market definition analysis are currently underway. The approach utilizes new survey instruments along with analysis that build upon past market research findings. The later approach incorporates several industry restructuring scenarios into the research assumptions. We believe these activities will provide the commercialization team with a fresh perspective on the changes taking place in the energy market. They will enable us to refine the market requirements previously defined to provide a MW-class MCFC power plant for distributed power generation, cogeneration, and compressor station applications.

The surveys and analysis address such issues as capacity, footprint, operating characteristics, interface requirements, and product trade-offs such as cost vs. efficiency. The results of the market surveys, in conjunction with applicable codes & regulations and design optimization will be analyzed to define preferred market entry power plant options. The results of these analysis are expected to be completed in the third quarter. The preferred power plant characteristics will be used to establish performance, life, and cost goals for the stack, mechanical skid equipment, and the power plant system. An ongoing technical progress evaluation are being maintained to measure development status compared to goals.

System Design and Analysis. This activity culminates in design and costing of a market-entry MW-class power plant. A preliminary baseline system has been selected against which trade-off studies will be performed. This baseline system expands upon design experience from Technology Development activities of the overall commercialization program.

Bechtel Corporation has developed design documents for the baseline system which include: a process flow diagram of the baseline design, complete with process flow characteristics (compositions, pressures, and temperatures); a description of the process; and a list of major equipment. Trade-off studies are being performed to determine the optimum operating parameters and process configuration for the market entry unit. Variables are independently changed to identify their impact on plant performance, reliability, and cost. Efficiency improvements will be weighed against increases in plant complexity, cost, size, reliability, and operating risk.

A design and cost estimate of the optimized plant has been generated. The cost estimates currently includes capital cost. Operating cost estimates and economic sensitivity analysis programs are being developed. The performance (design, off-design, and reliability, availability, maintainability, and safety) will be evaluated and dynamic simulations will be run to analyze the system behavior during normal and off-design conditions.

Manufacturing Process Development. The primary focus of this activity is to reduce the cost of M-C Power's MCFC stack. This effort will build on the component and stack manufacturing capabilities developed at M-C Power since 1989, the year in which we established our first manufacturing facility dedicated to developing full area MCFC . This facility has been producing full area components and test stacks since 1991. In 1994 the largest MCFC stack was manufactured and conditioned in the facility and subsequently shipped to Unocal's Research Center in Brea, California. M-C Power has also manufactured, assembled, conditioned, acceptance tested, and shipped a 250-kW stack to the Miramar Naval Air Station in San Diego, California.

The optimization and automation of active cell component manufacturing process, consolidation of in-house separator plate manufacturing, and upgrade of QA/QC and analytical laboratory capabilities will enhance cell component manufacturing for the prototype power plant. The identification, qualification, and implementation of advanced component formulations and manufacturing processes will further reduce cell costs for market entry.

The manufacturing processes developed will be used to prepare a conceptual design for M-C Power's market entry stack manufacturing facility. The conceptual design will include site and facility layouts, staffing requirements, inventory and throughput analysis, and manufacturing cost analysis.

Packaging and assembly. Techniques used for the assembly of the power plant affect cost, footprint, weight and heat loss from the plant. Stewart & Stevenson will build on their experience with packaging of the Unocal and San Diego Gas & Electric power plant units, along with their proven expertise with packaged power generation systems, to develop optimized packaging and assembly techniques.

Definition, verification, and implementation of packaging concepts and assembly methodologies will reduce the size and cost of the fuel cell power module, mechanical skid, and electrical module through efficient integration and assembly. Packaging concepts are being confirmed by scale models. The packaging concepts will be translated into three-dimensional computer models for verification of the assembly methodology and will be demonstrated in the MW class prototype power plant. The package design and assembly methodology will be translated into a conceptual factory design for commercial production.

Advanced component verification. To verify advanced components, cell assemblies, and commercial-area stacks the commercialization team is expanding upon its current infrastructure of testing facilities. This task involves maintenance of an existing 20 kW atmospheric pressure stack test facility and the 250 kW facility at Unocal. It also includes upgrade and maintenance of a 250 kW stack acceptance test facility, and construction of pressurized bench scale cell test facilities.

The commercialization team is developing, improving, and verifying the critical components and subsystems required in a market responsive MCFC product. Efforts will focus on the cell package, stack module, and balance-of-plant components, and detailed product design, packaging, and assembly.

Testing of cells and stacks will be carried out using facilities currently developed and will verify advanced engineering designs, component technologies and manufacturing processes. BOP components are being identified and qualified through strategic vendor alliances. Focus will be on the turbogenerator, recycle blower and power conditioner. Fuel processing will be addressed for a variety of alternate fuels. Finally, acceptance of all subsystems and BOP components will be achieved through factory assembly and testing of a prototype market entry power plant.

Accomplishments

A major milestone is within our grasp: completion of the Technology Development Phase of our commercialization program. Specifically, a 250 kW MCFC demonstration plant at the Naval Air Station Miramar in San Diego, California. This is the culminating event in our Product Development Test project. The project is currently on schedule for power plant operation in mid-October.

Through-out 1996, SDG&E has been preparing the site and installing the Balance-of-Plant major equipment. This includes an electrical and control building, the mechanical processing skid, and the natural gas reformer. M-C Power has successfully assembled, conditioned, acceptance tested and shipped a 250-cell MCFC stack to the site. The stack will be placed on its foundation at the site during the first week of August. Once process and control testing is completed, the fuel cell stack will be integrated with the BOP equipment and start-up procedures will begin. Demonstration testing is expected to last for approximately one year.

As completion of the PDT project approaches, accomplishments under the Product Design and Improvement Program are becoming apparent. This is due to our increasing focus on the activities pertained in the PDI program. The majority of the accomplishments to date have centered around improved performance of the cell components. Our focus has been to work on improvements at the component level as analysis work on the overall system progresses in parallel. This allows us to incorporate new findings into the analysis and is a reiterative process.

Progress in the cell performance is demonstrated in increased current density during cell testing. Reductions in cost are being realized through improvements in our matrix and electrode technology along with reducing parts and processing of separator plates.

Market definition activities are enabling us to refine our initial design criteria. Ongoing analysis will be completed by the end of the third quarter. The results will be incorporated into a detailed design of the market entry product.

Applications

Market Opportunities. The U.S. power generation industry is in the middle of evolutionary changes brought on by deregulation and increased competition, which creates both opportunities for the M-C Power MCFC power plant and uncertainty for the Team. This evolving marketplace needs advance power generation technologies, such as the molten carbonate fuel cell. This is driven by the industry's need to retain loads through better customer service, decreased capital

risks, incremental investments, stronger environmental regulations, and increased generation efficiency to balance the risk of escalating fuel prices.

Assessing and evaluating the market for M-C Power's fuel cell power plants is an important element of the Team's Commercialization Program. Understanding the evolving power generation industry helps ensure that the market entry product developed during the 1990s meets the expectations of our future customers and is responsive to marketplace requirements. Estimated market demand and product acceptance will aid M-C Power and the Team in establishing market entry strategies, manufacturing facilities, and financial requirements.

Segmentation. Market opportunities for stationary power generation can be divided into several categories based on the type of application, ownership, and/or operating strategy. Applications can be categorized by size, location, and function of the facility. The Team believes there is one principle market for its fuel cells during the initial ten years of commercial production. The market is distributed generation (<10 MW capacity). This segment includes electric-only sub-station applications, cogeneration opportunities within the commercial building and industrial sectors, improved customer service functions in the area of power quality and reliability, pipeline compressor stations, and specialty fuel sources (such as landfills, digesters, and renewable gasification processors). Common to everyone's view is that these small capacity generators must be strategically sited within the electric power distribution network. Selecting sites that provide added-value benefits above the electric capacity and energy they produce, allow distributed generators to compete with the commodity price of retail energy at the customer's site.

Product Requirements. The product definition activities over the past years have solicited marketplace inputs from the Alliance to Commercialize Carbonate Technology members. Surveys of industry representatives and economic evaluations of the marketplace have shaped the Team's perspective of market-responsive characteristics. First, the power plant must be durable and reliable in its intended applications. Second, it must be cost-effective to install, operate, and maintain. The power plant must produce electricity competitive with the 4 ¢/kWh to 7 ¢/kWh range typical in light industrial and commercial sectors. With the increasing competitive environment within the power industry, these characteristics must be achieved with the initial market entry power plants well before final product maturity.

Economic Analysis. Initial analysis has concluded that the projected MCFC power plant's cost of producing electricity is 6.7 ¢/kWh in electric-only applications with a fuel price of $4/MMBtu. This cost of electricity is reduced to 5.7 ¢/kWh in cogeneration applications and to 3.7 ¢/kWh when additional distribution system benefits are included. Additional economic analyses were conducted to assess the influence of varying capital cost, fuel prices, and operating capacity factors. With a fuel price at $2/MMBtu or with a capital cost approaching $1000/kW, the cost of electricity in typical cogeneration applications drops below the 5¢/kWh range.

Market Entry. Penetration analysis were completed to estimate the potential rate of market demand during the initial ten years of commercialization. Two cases were evaluated to represent a conservative and an aggressive penetration. In both cases the MCFC power plant captured a 4% maximum market share of the total installed U.S. generating capacity. Market capture followed a typical "S" shaped penetration curve beginning in 1999. In the conservative case the MCFC product reached its marketplace maturity 40 years after market entry, while under the

aggressive scenario maturity was achieved in 20 years. The results suggest that the MCFC market share could range from 300 MW/yr to over 1,000 MW/yr by 2005. Demand continues to increase with estimates ranging from 800 MW/yr to over 2,000 MW/yr by 2010. These penetration rates are greater than needed to establish a viable production business for the product. In fact, the Team's production estimates are below the conservative case to help ensure management of the technical and business risk associated with introducing an advanced technology product to the market.

Future Activities

Currently we are in the second year of a five year program with a goal of having a MCFC power plant product tested and available for commercial delivery within the program duration. There are many tasks that must be completed to ensure that our goal is met. Development work will continue in order to achieve our goal of increasing cell performance while simultaneously lowering component cost. Completion of the market and product definition activities that are currently underway will ensure that our final product design satisfies the changing needs of the electric power industry. These activities along with the data and results of the PDT demonstration project will be critical as we develop a detailed design of the market entry product.

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